

# Integral Field Spectroscopy of Mrk 273: Mapping $10^3$ km s $^{-1}$ Gas Flows and an Off-Nucleus Seyfert 2 Nebula<sup>1</sup>

Luis Colina<sup>2</sup>, Santiago Arribas<sup>3,4</sup> & Kirk D. Borne<sup>5</sup>

(2) *Instituto de Física de Cantabria (CSIC-UNICAN), Facultad de Ciencias, 39005*

*Santander, Spain (colina@ifca.unican.es)*

(3) *Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife Spain (sam@ll.iac.es)*

(4) *Consejo Superior de Investigaciones Científicas (CSIC)*

(5) *Raytheon Information Technology and Scientific Services, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA (borne@rings.gsfc.nasa.gov)*

<sup>1</sup>

Received \_\_\_\_\_; accepted \_\_\_\_\_

---

<sup>1</sup> Based on observations with WHT operated on the island of La Palma by the ING in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

## ABSTRACT

Integral field optical spectroscopy with the INTEGRAL fiber-based system is used to map the extended ionized regions and gas flows in Mrk 273, one of the closest Ultraluminous Infrared galaxies (ULIRGs).

The  $H\beta$  and  $[\text{OIII}]\lambda 5007\text{\AA}$  maps show the presence of two distinct regions separated by  $4''$  (3.1 kpc) along position angle (PA)  $240^\circ$ . The northeastern region coincides with the optical nucleus of the galaxy and shows the spectral characteristics of LINERs. The southwestern region is dominated by  $[\text{OIII}]$  emission and is classified as a Seyfert 2. Therefore, in the optical, Mrk 273 is an ultraluminous infrared galaxy with a LINER nucleus and an extended off-nucleus Seyfert 2 nebula.

The kinematics of the  $[\text{OIII}]$  ionized gas shows (i) the presence of highly disturbed gas in the regions around the LINER nucleus, (ii) a high-velocity gas flow with a peak-to-peak amplitude of  $2.4 \times 10^3 \text{ km s}^{-1}$ , and (iii) quiescent gas in the outer regions (at 3 kpc).

We hypothesize that the high-velocity flow is the starburst-driven superwind generated in an optically obscured nuclear starburst, and that the quiescent gas is directly ionized by a nuclear source, like the ionization cones typically seen in Seyfert galaxies.

*Subject headings:* galaxies: active — galaxies: individual (Markarian 273) — galaxies: interactions — galaxies: nuclei — galaxies: starburst — galaxies: Seyfert

## 1. INTRODUCTION

Ultraluminous infrared galaxies (ULIRGs), with bolometric luminosities ( $L_{IR} \simeq L_{bol} \geq 10^{12} L_{\odot}$ ), are the brightest galaxies in the local universe. ULIRGs show signs of strong interactions or mergers and have large amounts of gas and dust that significantly obscure the nuclear ionizing sources (see Sanders & Mirabel 1996 for a review). Mid-infrared spectroscopy has shown that ULIRGs with optical HII- and LINER-like spectra are dominated by the energy output from nuclear starbursts (Lutz *et al.* 1998; Genzel *et al.* 1999; Lutz, Veilleux, & Genzel 1999). However, the increased fraction of active galactic nuclei (AGN) among the brightest ULIRGs ( $L_{IR} \geq 10^{12.3} L_{\odot}$ ) is taken as evidence for the presence of a dust-enshrouded quasar powering these galaxies, at least at the brightest end of the luminosity distribution (Veilleux, Kim, & Sanders 1999).

Two-dimensional kinematical studies of a few ULIRGs (Mihos & Bohun 1998) show that the ionized gas in these galaxies has a wide variety of features affected by several factors, such as the interaction stage, the gas content, and the effects of massive starbursts.

The study of compact galaxies like ULIRGs showing complex velocity fields and ionization substructures requires the use of two-dimensional spectroscopy (i.e. integral field) to characterize and map simultaneously the warm ionized gas, the cold dust, and the stellar component.

Mrk 273 is one of the closest ULIRGs ( $z = 0.03778$ ; Downes, Solomon & Radford 1993). It is characterized by a long nearly straight tidal tail, a LINER (Veilleux *et al.* 1995) or Seyfert 2 type optical spectrum (Sanders *et al.* 1988; Veilleux, Kim, & Sanders 1999), and possibly the presence of a nuclear starburst (Genzel *et al.* 1998; Lutz, Veilleux, & Genzel 1999). The nuclear region of Mrk 273 is very dusty and mottled, showing a very strong dust lane and a system of radially extended filaments similar to those seen in M82 (Borne *et al.* 1999). Mrk 273 has two near-infrared nuclei separated by  $\sim 1''$  (Majewski *et al.* 1993;

Knapen *et al.* 1997; Scoville *et al.* 1999).

In this letter we highlight the new results obtained for Mrk 273 integral field optical spectroscopy. The observations and reduction procedures are briefly mentioned in section §2, and the results are presented in section §3. Throughout the paper a Hubble constant of  $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$  is assumed.

## 2. OBSERVATIONS AND DATA REDUCTION

Integral field spectroscopy of Mrk 273 was obtained with the INTEGRAL system (Arribas *et al.* 1998), a fiber-based spectrograph mounted at the Naysmith No. 1 platform of the 4.2m William Herschel Telescope. Although this system has several fiber bundles, the one used for the present observations consisted of 219 fibers, each  $0.9''$  in diameter and covering a field-of-view of  $16.5'' \times 12.3''$ . The spectra were taken using a 600 l/mm grating, covering the 5000-7900 Å range, and with an effective resolution of 4.8 Å. The total integration time was 4500 seconds, split into three separate integrations of 1500 seconds each. The seeing had a value of  $\sim 1.0''$ .

The reduction consists of two main steps: (i) basic reduction of the spectra, and (ii) generation of continuum and emission-line images from the reduced spectra (see Colina & Arribas 1999 for details). The [OIII]5007Å profiles obtained *simultaneously* with INTEGRAL for the central region of Mrk 273 are shown in Figure 1 as an example of the kind of reduced data obtained after step (i) is finished. These represent only a small 60Å subsample of the full 5000-7900 Å spectral coverage obtained at each of the 219 fiber locations.

## 3. RESULTS AND DISCUSSION

### 3.1. A LINER Nucleus with an Off-nucleus Seyfert 2 Nebula

Mrk 273 has been classified as a LINER (Veilleux *et al.* 1995) and a Seyfert 2 (Veilleux, Kim & Sanders 1999). These authors attribute the change in the classification as due to differences in the extraction apertures, suggesting therefore the existence of extended ionized gas in this galaxy.

Our data show that the stellar light distribution and the warm line-emitting gas have a rather different morphology (see Figure 2). The stellar blue light distribution has a main nucleus, with a secondary faint nucleus about  $4''$  south of it. The stellar component is distributed along the North-South direction showing in the northern part an elongation that marks the beginning of the well known tidal tail of this galaxy (see bottom left panel in Figure 2).

By contrast, the ionized gas is distributed into two well differentiated high surface brightness regions located along  $\text{PA}=240^\circ$ , and with their emission peaks separated by about  $4''$  (*i.e.*,  $\sim 3.1$  kpc). Two additional regions, at lower surface brightness, are also identified. The first of these is located at about  $3.5''$  east of the main northeastern region while the second one appears as a tongue about  $2''$  south of the main southwestern region (see left and middle top panels in Figure 2).

The northeastern  $\text{H}\beta$ -emitting region coincides with the blue continuum nucleus of the galaxy, while the southwestern  $[\text{OIII}]$ -emitting region lies outside the main stellar body of the galaxy and is not associated with any distinct source seen in the blue continuum. As in Arp 220 (Scoville *et al.* 1998) and other ULIRGs (Evans 1999), the observed optical structure of Mrk 273 is very much affected by the dust lanes clearly visible in *HST* images (Borne *et al.* 1999). Comparisons of *HST* *I*-band and near-infrared images (Colina, unpublished) show that the optical nucleus is offset from the two well known near-infrared nuclei (Majewski *et al.* 1993; Knapen *et al.* 1997; Scoville *et al.* 1999) by  $\sim 0.6''$  (0.47 kpc)

and  $\sim 1.5''$  (1.18 kpc) along PA45 and PA43, respectively. Therefore the optical nucleus and the ionized regions detected here correspond to clouds of interstellar gas being ionized by the obscured ionizing nuclear source(s) associated most likely with the near-infrared nuclei.

The two main line-emitting regions are characterized by different excitation conditions as suggested by the observed variations in their relative  $H\beta$  and [OIII] surface brightnesses (Figure 2 & 3). Based on the observed  $H\alpha/H\beta$  ratio, the northeastern line-emitting region has an internal extinction of 3.4 magnitudes in the visual. After correcting for extinction, this region presents the spectral characteristics of a LINER ([OIII]/ $H\beta$  = 0.26 dex, [OI]/ $H\alpha$  =  $-0.84$ , [NII]/ $H\alpha$  =  $-0.09$  and [SII]/ $H\alpha$  =  $-0.33$ ). On the other hand, the high-excitation off-nuclear [OIII]-emitting region shows no evidence for internal extinction by dust and its emission line ratios are characteristic of a Seyfert 2 ([OIII]/ $H\beta$  = 0.88 dex, [OI]/ $H\alpha$  =  $-0.96$ , [NII]/ $H\alpha$  = 0.0 and [SII]/ $H\alpha$  =  $-0.32$ ).

Our new data show that, in the optical, Mrk 273 has a LINER nucleus and an off-nucleus Seyfert 2 extended nebula located at about 3.1 kpc southwest of the nucleus. However, the optical nucleus is offset from the two near-infrared nuclei. Moreover, *HST* NICMOS near-infrared images (Scoville *et al.* 1999) show that the northern near-infrared nucleus (*i.e.*, the one closest to our LINER nucleus) is extended (starburst?) while the southern nucleus is a *K*-band point-like source (AGN?), with a size less than  $0.15''$  ( $\leq 120$  pc). Also, the extinction derived in the mid-infrared ( $A_V \geq 15$ ; Genzel *et al.* 1998) is a factor  $\sim 5$  larger than that measured in the optical, while the mid-infrared spectrum shows the spectral characteristics of an AGN (Taniguchi *et al.* 1999) and the presence of the starburst-like  $7.7 \mu\text{m}$  PAH (polycyclic aromatic hydrocarbon) emission (Genzel *et al.* 1998; Lutz, Veilleux, & Genzel 1999).

Based on our new results and previously published results, we hypothesize that the optical LINER-like nucleus is in fact a region of the galaxy close to, and ionized by, the

extended (starburst?) near-infrared nucleus while the Seyfert 2 nebula is directly ionized by the  $K$ -band point-like nucleus (dust-enshrouded AGN?).

### 3.2. Detection and Mapping of High-Velocity Gas Flows

The profiles of the [OIII] 5007Å emission line show substructures like double peaks, blue and red bumps, indicating the presence of at least one additional velocity component in a large region around the LINER-like nucleus (see Figure 1 to visualize the changes in the profile). We have decomposed these profiles into two gaussian components in order to detect the presence of coherent gas flows over large regions and to map their spatial distribution and velocity field. The light distribution and velocity field of these two components are presented in Figure 2 (middle and right panels, respectively), where the [OIII] velocity measured in the optical nucleus ( $11250 \text{ km s}^{-1}$ ) has been subtracted.

The primary [OIII] component (called component A in Figure 2) has a spatial distribution coincident with that of the low-excitation  $H\beta$ -emitting gas, including the low surface brightness tongue located south of the brightest [OIII]-emitting peak. The velocities displayed by this gas have an amplitude (peak-to-peak) of about  $400 \text{ km s}^{-1}$ . This [OIII] component also has a wide profile with values (FWHM) ranging from  $\sim 400$  to  $600 \text{ km s}^{-1}$ , similar to the line widths of several other luminous and ultraluminous infrared galaxies (Heckman *et al.* 1990). Thus, the kinematics of the ionized gas associated with the optical LINER nucleus and surrounding regions is very complex and appears to be highly disturbed.

The secondary [OIII] component (called component B in Figure 2) is energetically a minor contributor, but on the contrary shows large velocities (see bottom right panel in Figure 2) and has a spatial structure well differentiated from that of the [OIII] primary component and low-excitation gas (see bottom middle panel in Figure 2). The velocity

field of this component has one of the largest velocity amplitudes ( $2.4 \times 10^3 \text{ km s}^{-1}$ , peak-to-peak) measured in luminous infrared galaxies (cf. NGC 3079; Veilleux *et al.* 1994) and ULIRGs. The maximum velocity gradient of the flow is detected along PA135, and its dynamical center does not coincide with the optical nucleus, but it is offset by about  $1'' \pm 0.5''$  to the southwest. The extended near-infrared nucleus observed in the NICMOS images (Scoville *et al.* 1999) is located about  $0.6''$  southwest (PA225) of the optical nucleus. If this *K*-band nucleus traces a nuclear starburst, the high-velocity flows detected here could then be the associated starburst-driven superwind similar to those detected in other luminous infrared galaxies (Heckman *et al.* 1990; Colina, Lipari, & Macchetto 1991).

Finally, the ionized gas in the off-nucleus Seyfert 2 nebula is blueshifted by 100–200  $\text{km s}^{-1}$  with respect to the velocity of the optical nucleus, shows no evidence for coherent flows (peak-to-peak velocity amplitude of less than  $100 \text{ km s}^{-1}$ ), and has a narrow profile ( $\text{FWHM} \leq 260 \text{ km s}^{-1}$ ). These properties are consistent with interstellar gas in a quiescent state, located in the outer regions of the galaxy, and not affected by either starburst- or AGN-related gas flows. These characteristics are reminiscent of the ionized gas detected in the extended, kiloparsec size, ionization cones of some Seyfert 2 galaxies.

#### 4. SUMMARY

The excitation conditions and kinematics of the emission line gas in the ultraluminous infrared galaxy Mrk 273 have been investigated on the basis of integral field optical spectroscopy. The new data have shown that the ionized gas in Mrk 273 has an extended structure formed by two main emitting regions. The first region coincides with the optical nucleus and has the spectral characteristics of a low-luminosity LINER. The second region is located at a distance of  $4''$  (3.1 kpc) southwest of the nucleus, and is classified as a Seyfert 2.



The profile of the [OIII] line presents double peaks indicating the existence of at least two dynamical components. The primary, energetically dominant, component reveals highly disturbed gas around the LINER nucleus. A secondary high-velocity gas flow ( $2.4 \times 10^3 \text{ km s}^{-1}$ , peak-to-peak amplitude) is seen as evidence for a starburst-driven superwind generated in a dust-obscured nuclear starburst.

The [OIII] ionized gas in the Seyfert 2 nebula has the properties of quiescent interstellar gas located in the outer regions of the galaxy and being directly ionized by a dust-enshrouded AGN, similar to the ionization cones of Seyfert 2 galaxies.

Luis Colina thanks the Instituto de Astrofísica de Canarias for its hospitality and financial support. Kirk Borne thanks Raytheon for providing financial support during his Sabbatical Leave. Support for this work was provided by NASA through grant number GO-06346.01-95A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555.

Fig. 1.— The final calibrated  $[\text{OIII}]\lambda 5007\text{\AA}$  profiles obtained with INTEGRAL are shown. The bundle of fibers cover a projected size of  $16.5'' \times 12.3''$  on the sky, and the numbers in the plot indicate the number of the fiber at the entrance of the spectrograph (*i.e.*, pseudo-slit). The substructure and double peaks in several of the fibers (69, 80, 91, 92, 112, 133, etc.) are clearly visible.

Fig. 2.— Images of the stellar component and ionized gas as traced by the blue continuum (bottom left panel),  $\text{H}\beta$  line emission (top left panel), and  $[\text{OIII}]\lambda 5007\text{\AA}$  line emission (middle panels). The velocity fields for the two  $[\text{OIII}]\lambda 5007\text{\AA}$  components are also shown (right panels), clearly indicating the high-velocity gas flows detected in component B (see §3 for details). The scales of each of the intensity maps were selected independently and are in arbitrary units.

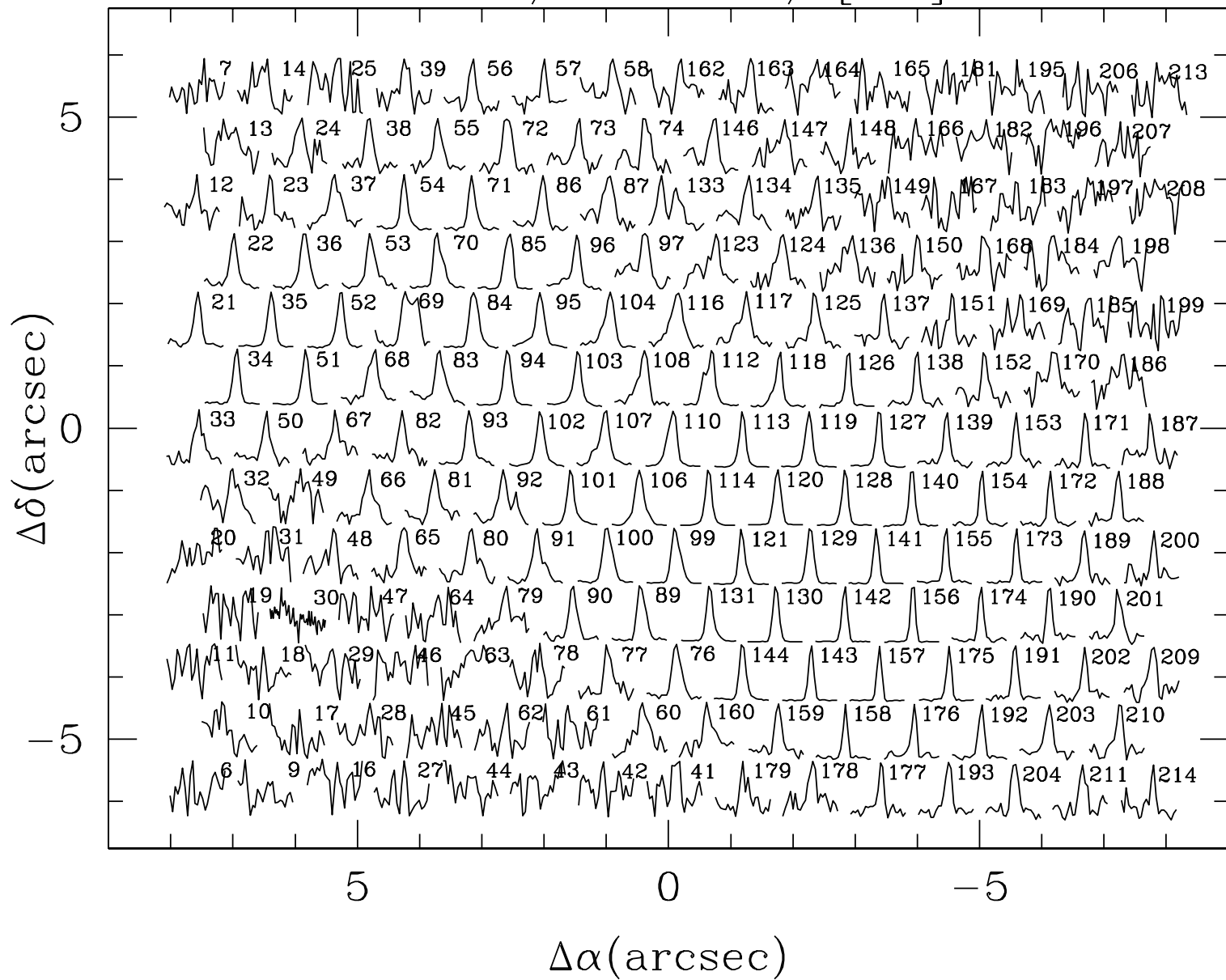
Fig. 3.— Plot showing the spectral regions of fibers 95 and 120 corresponding to the peak emission of the two main line-emitting regions: the northeastern nuclear  $\text{H}\beta$  and the southwestern off-nucleus  $[\text{OIII}]$  regions, respectively. The spectra clearly show the LINER- and Seyfert2-like spectral characteristics for the nucleus and off-nucleus regions, respectively. Note that the horizontal axis does not represent a continuous range in wavelength, but two subsets corresponding to the  $\text{H}\beta/[\text{OIII}]$  and  $\text{H}\alpha/[\text{NII}] + [\text{SII}]$  emission lines

## REFERENCES

- Arribas, S. Carter, D., Cavaller, L., del Burgo, C., Edwards, R., Fuentes, J., García, A., Gentles, B., Herreros, J. M., Jones, L., Mediavilla, E., Pi, M., Pollacco, D., Rees, P., & Sosa, N. 1998 SPIE, 3355, 821.
- Borne, K., Bushouse, H., Colina, L., & Lucas, R. 1999, ApJS, submitted
- Colina, L., & Arribas, S. 1999, ApJ 514, 637
- Colina, L., Lipari, S., & Macchetto, F. 1991, ApJ 379, 113
- Downes, D., Solomon, P.M., & Radford, S.J.E. 1993, ApJ 414, L13
- Evans, A.S. 1999, Ap&SS, in press
- Genzel, R., Lutz, D., Sturm, E., Egami, E., Kunze, D., Moorwood, A.F.M., Rigopoulou, D., Spoon, H.W.W., Sternberg, A., Tacconi-Garman, L.E., Tacconi, L., & Thatte, N. 1998, ApJ 498, 579
- Heckman, T.M., Armus, L., & Miley, G.K. 1990, ApJS 74, 833
- Knapen, J.H., Laine, S., Yates, J.A., Robinson, A., Richards, A.M.S., Doyon, R., & Nadeau, D. 1997, ApJ 490, L29
- Lutz, D., Spoon, H.W.W., Rigopoulou, D., Moorwood, A.F.M., & Genzel, R. 1998, ApJ 505, L103
- Lutz, D., Veilleux, S., & Genzel, R. 1999, ApJ 517, L13
- Majewski, S.R., Hereld, M., Koo, D.C., Illingworth, G.D., & Heckman, T.M. 1993, ApJ 402, 125
- Mihos, J.C., & Bothun, G.D. 1998, ApJ 500, 619

- Sanders, D., & Mirabel, I.F. 1996, *AR&AA* 34, 749
- Sanders, D., Soifer, B.T., Elias, J.H., Madore, B.F., Matthews, K., Neugebauer, G., & Scoville, N.Z. 1988 *ApJ*, 325, 74
- Scoville, N.Z., Evans, A.S., Dinshaw, N., Thompson, R., Rieke, M., Schneider, G., Low, F.J., Hines, D., Stobie, B., Becklin, E., & Epps, H. 1998, *ApJ* 492, L107
- Scoville, N.Z., Evans, A.S., Thompson, R., Rieke, M., Hines, D., Low, F.J., Dinshaw, N., Surace, J.A., & Armus, L. 1999, *AJ*, submitted
- Taniguchi, Y., Yoshino, A., Ohyama, Y., & Nishiura, S. 1999, *ApJ* 514, 660
- Veilleux, S., Cecil, G., Bland-Hawthorn, Tully, R.B., Filippenko, A.V., & Sargent, W.L.W. 1994, *ApJ* 433, 48
- Veilleux, S., Kim, D.C., Sanders, D.B., Mazzarella, J.M., & Soifer, B.T. 1995, *ApJS* 98, 171
- Veilleux, S., Kim, D.C., & Sanders, D.B. 1999, *ApJ*. in press (astro-ph/9904149)

# INTEGRAL / Mrk 273 / [OIII] $\lambda 5007$



# INTEGRAL– Mrk 273

